Fault tree and Markov analysis applied to various design complexities

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Fault Tree and Markov Analysis Applied to Various Design Complexities
J.D. Andrews, PhD; Department of Mathematical Sciences, Loughborough University, England
Clifton A. Ericson II, The Boeing Company; Seattle, Washington

Abstract
Fault Tree Analysis (FTA) and Markov Analysis (MA) are two analysis techniques that have been around for many years. Both are well proven techniques, each having its advantages and disadvantages. One of the common questions in industry is whether or not both modeling tools are adequate for a design application, or if one tool has an advantage over the other. This is a significant question, because there are many different types of system design complexities, many different types of undesired system states, and many different size system problems, all of which have a consequential impact on the analysis tool utilized.

There are some very important questions that need to be answered in order for the systems analyst to perform a proper evaluation of a system design. For instance, can both tools handle all of the various design complexities? Do both tools provide accurate results for all cases? Do both tools handle repair? Do both tools handle catastrophic and non-catastrophic events? Are approximation results good enough? Can both tools handle large systems?

This paper describes the various types of common system design complexities and compares the FTA and MA approaches for each of these system configurations. The results of these two approaches are then compared, providing some relative conclusions.

Design Complexities
System analysis is a challenging process due to the various types of design types, complexities and factors involved in today's modern complex systems. As system design advances along with advances in technology, the corresponding complexity also advances and increases. With increased complexity, it also becomes more difficult to analyze and predict system behavior and especially system misbehavior.

Table 1 contains a list of the major factors that cause complexity in both systems design and systems analysis. Each one of these factors presents a different issue, both for designers and systems analysts trying to evaluate the design. The complexity issue of Design Type is the primary issue being addressed by this paper. Table 2 provides the relevant supporting information for the probability calculations.

<table>
<thead>
<tr>
<th>Complexity Factors</th>
<th>Consideration</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Design Type</td>
<td>Affects model correctness</td>
</tr>
<tr>
<td>2 Design Size</td>
<td>Affects modeling tools and model correctness</td>
</tr>
<tr>
<td>3 Exposure Time</td>
<td>Affects model and probability calculation</td>
</tr>
<tr>
<td>4 Latency</td>
<td>Affects model and probability calculation</td>
</tr>
<tr>
<td>5 Repair</td>
<td>Affects probability calculation</td>
</tr>
<tr>
<td>6 Dependency</td>
<td>Affects model correctness</td>
</tr>
<tr>
<td>7 Logic Loops</td>
<td>Affects model correctness</td>
</tr>
<tr>
<td>8 Accuracy</td>
<td>Affects model capabilities (approximations)</td>
</tr>
<tr>
<td>9 Undesired States</td>
<td>States range from hazardous to unavailable</td>
</tr>
<tr>
<td>10 System Criticality</td>
<td>States range from safety critical to safe</td>
</tr>
<tr>
<td>11 Standby Redundancy</td>
<td>Hot, warm, cold - model correctness</td>
</tr>
<tr>
<td>12 Coverage</td>
<td>Affects model and probability calculation</td>
</tr>
</tbody>
</table>

Tables 3 through 8 contain an analysis of each design type. These tables describe the design type and operation, and present both the Fault Tree and Markov model for each. These tables describe the major design type categories and their corresponding philosophy of operation. Each design type is individual and unique, and each requires its own concomitant model. The analysis problem often cascades as different design types are combined together in an overall system. Some design types are easier to model than others.
**Table 2 – Supporting Data**

<table>
<thead>
<tr>
<th>Notation</th>
<th>Event Probability Calculation</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\lambda_A$ = failure rate of A (also $\lambda A$ in some places)</td>
<td>$q_A = \frac{\lambda_A}{\lambda_A + v_A} \left(1 - e^{-[\lambda_A + v_A]T} \right)$</td>
</tr>
<tr>
<td>$v_A$ = repair rate of A</td>
<td>$q_B = \frac{\lambda_B}{\lambda_B + v_B} \left(1 - e^{-[\lambda_B + v_B]T} \right)$</td>
</tr>
<tr>
<td>$A_W$ = working</td>
<td>no repair when $v_A = v_B = 0$</td>
</tr>
<tr>
<td>$A_F$ = failed</td>
<td></td>
</tr>
<tr>
<td>$\overline{\lambda_A}$ = failure rate of A in standby</td>
<td></td>
</tr>
</tbody>
</table>

**Table 3 – System Description**

A system is comprised of two components A and B in series. System success requires that both must operate successfully at the same time. System failure occurs if either one or both fail.

**FTA Solution**

$\begin{align*}
q_A &= \frac{\lambda_A}{(\lambda_A + v_A)} \left(1 - e^{-[\lambda_A + v_A]T} \right) \\
q_B &= \frac{\lambda_B}{(\lambda_B + v_B)} \left(1 - e^{-[\lambda_B + v_B]T} \right) \\
Q_{yx} &= q_A + q_B - q_A q_B
\end{align*}$

- System fails
- A fails
- B fails

with repair:

$P = P_A + P_B - P_A P_B$

$= (\frac{\lambda_A}{(\lambda_A + v_A)} \left(1 - e^{-[\lambda_A + v_A]T} \right) + (\frac{\lambda_B}{(\lambda_B + v_B)} \left(1 - e^{-[\lambda_B + v_B]T} \right) - [(\frac{\lambda_A}{(\lambda_A + v_A)} \left(1 - e^{-[\lambda_A + v_A]T} \right) \right) \frac{\lambda_B}{(\lambda_B + v_B)} \left(1 - e^{-[\lambda_B + v_B]T} \right)]

without repair ($v_A = v_B = 0$):

$P = [1 - e^{-\lambda A T}] + [1 - e^{-\lambda B T}] - [1 - e^{-\lambda A T}] [1 - e^{-\lambda B T}]

= 1 - e^{-[(\lambda A + \lambda B)T]}$

**Markov Solution**

$\begin{align*}
dP_1/dt &= -(\lambda_A + \lambda_B)P_1 + v_A P_2 + v_B P_3 \\
dP_2/dt &= \lambda_A P_1 - (\lambda_A + v_A)P_2 + v_B P_4 \\
dP_3/dt &= \lambda_B P_1 - (\lambda_A + v_A)P_3 + v_A P_4 \\
dP_4/dt &= \lambda_B P_2 + \lambda_A P_3 - (v_A + v_B)P_4 \\
P &= P_2 + P_3 + P_4
\end{align*}$

$P = 1 - e^{-[(\lambda A + \lambda B)T]}$

no repair case ($v_A = v_B = 0$)

**Conclusion**

Both methods provide the same results (i.e., the equations are identical). Derivation of the repair calculations for the MA are not shown here due to the complexity and space required.
Table 4—Parallel System

Design Type Description
A system is comprised of two components A and B in parallel. System success requires that either one (or both) must operate successfully. System failure occurs only if both fail are failed at the same time.

FTA Solution

\[ q_A = \frac{\lambda_A}{(\lambda_A + v_A)} \left( 1 - e^{-(\lambda_A + v_A)T} \right) \]
\[ q_B = \frac{\lambda_B}{(\lambda_B + v_B)} \left( 1 - e^{-(\lambda_B + v_B)T} \right) \]
\[ Q_{MT} = q_A \cdot q_B \]

with repair:
\[ P = P_A \cdot P_B \]
\[ = \frac{\lambda_A}{(\lambda_A + v_A)} \left( 1 - e^{-(\lambda_A + v_A)T} \right) \cdot \frac{\lambda_B}{(\lambda_B + v_B)} \left( 1 - e^{-(\lambda_B + v_B)T} \right) \]

without repair (\(v_A = v_B = 0\)):
\[ P = (1 - e^{-\lambda_A T}) (1 - e^{-\lambda_B T}) \]

Markov Solution

\[ \begin{align*}
\lambda_A & \quad \lambda_B \\
A, B & \quad 2 \\
A_W, B_W & \quad \lambda_A \quad \lambda_B \\
1 & \quad v_A \quad v_B \\
4 & \quad A_W, B_F \\
3 & \quad v_A \quad v_B \\
\end{align*} \]

\[ \begin{align*}
dP_1 / dt & = - (\lambda_A + \lambda_B) P_1 + v_A P_2 + v_B P_3 \\
dP_2 / dt & = \lambda_A P_1 - (\lambda_A + v_A) P_2 + v_B P_4 \\
dP_3 / dt & = \lambda_B P_1 - (\lambda_B + v_B) P_3 + v_A P_4 \\
dP_4 / dt & = \lambda_B P_2 + \lambda_A P_3 - v_A P_4 \\
P & = P_4 \\
\end{align*} \]

\[ P = (1 - e^{-\lambda_A T})(1 - e^{-\lambda_B T}) \quad \text{no repair case (}v_A = v_B = 0\text{)} \]

Conclusion
Both methods provide the same results (i.e., the equations are identical). Derivation of the repair calculations for the MA are not shown here due to the complexity and space required.
Table 5 – Sequence Parallel System

Design Type Description
A system is comprised of two components A and B. System success requires that both must operate successfully at the same time. System failure occurs if both fail, but only if A fails before B.

FTA Solution

\[
P = \frac{(P_A \cdot P_B)}{N!} \quad \text{General equation, where } N \text{ is number of inputs and } P_A = P_B.
\]

\[
P = \frac{(P_A \cdot P_B)}{2}
= \frac{((1 - e^{\lambda A}))((1 - e^{\lambda B}))}{2}
\quad \text{no repair case (v_a = v_b = 0)}
\]

Markov Solution

\[
P = \frac{\lambda_A(1 - e^{\lambda B}) - \lambda_B(e^{\lambda B} - e^{(\lambda A + \lambda B)T})}{\lambda_A + \lambda_B}
\quad \text{no repair case (v_a = v_b = 0)}
\]

Conclusion
Resulting equations are different, making the FT equation an approximation. Refer to Figure 1 for a graphical comparison of results.

Figure 1 – Comparison of Results for Sequence Parallel System
(Where \(\lambda_A = 1.0 \times 10^{-6}\) and \(\lambda_B = 1.0 \times 10^{-7}\))

<table>
<thead>
<tr>
<th>Time (Hrs)</th>
<th>FTA</th>
<th>MA</th>
<th>MA</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>5.00000 E-14</td>
<td>5.00000 E-14</td>
<td>5.00000 E-14</td>
</tr>
<tr>
<td>10</td>
<td>4.99947 E-12</td>
<td>4.99998 E-12</td>
<td>4.99998 E-12</td>
</tr>
<tr>
<td>100</td>
<td>4.99973 E-10</td>
<td>4.99980 E-10</td>
<td>4.99980 E-10</td>
</tr>
<tr>
<td>1,000</td>
<td>4.99725 E-8</td>
<td>4.99800 E-8</td>
<td>4.99800 E-8</td>
</tr>
<tr>
<td>10,000</td>
<td>4.97260 E-6</td>
<td>4.98006 E-6</td>
<td>4.98006 E-6</td>
</tr>
<tr>
<td>100,000</td>
<td>4.73442 E-4</td>
<td>4.80542 E-4</td>
<td>4.80542 E-4</td>
</tr>
<tr>
<td>1,000,000</td>
<td>3.00771 E-2</td>
<td>3.45145 E-2</td>
<td>3.45145 E-2</td>
</tr>
<tr>
<td>10,000,000</td>
<td>3.16046 E-1</td>
<td>5.41213 E-1</td>
<td>5.41213 E-1</td>
</tr>
<tr>
<td>100,000,000</td>
<td>4.99977 E-1</td>
<td>9.09046 E-1</td>
<td>9.09046 E-1</td>
</tr>
<tr>
<td>1,000,000,000</td>
<td>4.99977 E-1</td>
<td>9.09046 E-1</td>
<td>9.09046 E-1</td>
</tr>
</tbody>
</table>
### Table 6: Full Monitor System

**Design Type Description**

A system is comprised of two components, Monitor A and component B. Monitor A monitors the operation of B. If it detects any failure in B it takes corrective action. System success requires that B must operate successfully. System failure occurs if component B fails, which can only happen if Monitor A fails to detect a problem with B, and B subsequently fails. If A works it always corrects any failure in B or provides a warning.

![Diagram of system](image)

**FTA Solution**

- **System Fails**
  - **Monitor A Fails**
  - **B Fails**

\[
P = \frac{(P_A \cdot P_B)}{2} = \frac{((1 - e^{-\lambda AT})(1 - e^{-\lambda BT})}{2}
\]

no repair case \( (v_A = v_B = 0) \)

[Same as Table 5]

**Markov Solution**

\[
P = \frac{\lambda_A(1 - e^{-\lambda BT}) - \lambda_B(e^{-\lambda BT} - e^{(\lambda_A+\lambda_B)T})}{\lambda_A + \lambda_B}
\]

no repair case \( (v_A = v_B = 0) \)

[Same as Table 5]

**Conclusion**

Resulting equations are different, making the FT equation an approximation. Refer to Figure 1 for a graphical comparison of results.
### Table 7 – Partial Monitor System (Coverage)

**Design Type Description**

A system is comprised of two components, Monitor A and component B. Monitor A monitors the operation of B, however, it is only designed to monitor 80% of B. If it detects any failure in B it takes corrective action. System success requires that B must operate successfully. System failure occurs if component B fails, which can only happen if Monitor A fails to detect a problem with the monitored portion of B, or if the unmonitored portion of B fails.

![Diagram showing system components](image)

Note – the darker portion of B is not monitored ($\lambda_{B1}$).

### FTA Solution

\[
P = P_{B1} + \frac{P_{A} P_{B2}}{2} + \frac{(1 - e^{-\lambda_{B1} T}) + ((1 - e^{-\lambda_{AT}})(1 - e^{-\lambda_{B2} T}) / 2 - [(1 - e^{-\lambda_{B1} T})(1 - e^{-\lambda_{AT}})(1 - e^{-\lambda_{B2} T})] / 2}{2}
\]

no repair case ($v_A = v_B = 0$)

### Markov Solution

### Conclusion

This is a coverage type problem, whereby the monitor does not provide complete coverage of the circuit being monitored. The FTA solution is shown here, but the MA solution is too complex to show in the allotted space.
Table 8 – Standby System

Design Type Description
A system is comprised of two main components A and B, and a monitor. System operation starts with component A in operation and B on standby. If A fails, then B is switched on-line and it takes over. System success requires that either A or B operate successfully. System failure occurs if both components A and B fail. Note that B can be failed if switching fails to occur.

There are three classes of Standby systems:
- Hot Standby - powered during standby (uses operational $\lambda_0$)
- Warm Standby - partially powered during standby ($\lambda_w < \lambda_0$)
- Cold Standby - un-powered during standby ($\lambda_c = 0$)

FTA Solution

System Fails

A Fails

\[ \lambda_A \]

B Not Available

B Fails

B Fails In Standby

B Fails During Op

B Not Switched

Switching Fails

Monitor Fails

\[ \lambda_M \]

\[ \lambda_\beta_1 \]

\[ \lambda_\beta_2 \]

\[ \lambda_\gamma \]

\[ P = P_A \cdot (P_{\beta_1} + P_{\beta_2} + P_M + P_S) \]

\[ P = P_A P_{\beta_1} + P_A P_{\beta_2} + P_A P_M + P_A P_S \]

Simplified model assuming monitor is perfectly reliable.

\[ P = P_A \cdot (P_{\beta_1} + P_{\beta_2}) \cdot (1 - e^{-\lambda_M T}) \cdot ((1 - e^{-\lambda_{\beta_1} T}) + (1 - e^{-\lambda_{\beta_2} T})) \]

Markov Solution (warm standby)

\[ \begin{align*}
2 \quad A_{SW}, B_{SW} \\
3 \quad A_{FW}, B_{FW} \\
4 \quad A_{WF}, B_{WF} \\
5 \quad A_{WF}, B_{WF} \\
\end{align*} \]

\[ \begin{align*}
dP_1 / dt &= - (\lambda_A + \lambda_\beta_1) P_1 + v_A P_4 \\
dP_2 / dt &= - (\lambda_A + \lambda_\beta_2) P_2 + v_A P_3 \\
dP_3 / dt &= \lambda_A P_1 + \lambda_\beta_1 P_2 - (\lambda_A + v_A) P_3 + v_0 P_4 \\
dP_4 / dt &= \lambda_A P_1 + \lambda_\beta_2 P_2 - (\lambda_A + v_A) P_4 - (v_A + v_B) P_5 \\
dP_5 / dt &= \lambda_B P_3 + \lambda_A P_4 - (v_A + v_B) P_5 \\
\end{align*} \]

\[ P = ? \]

Simplified model assuming monitor is perfectly reliable.

Conclusion
The Markov model is much more difficult when the Monitor is not 100% reliable, therefore it is modeled assuming it works perfectly for this example, but the Fault Tree is able to model the real life situation where the Monitor is fallible. Quite often the exposure time is different for operating, hot, warm and cold standby modes. When in Hot Standby $\lambda_A = \lambda_A$ and the Fault Tree and Markov solutions are identical. When in Cold Standby $\lambda_A = 0$. For Warm Standby and Cold Standby the Fault Tree solutions are approximations.
Example FT of System Model

The following is a larger system design that combines together several of the basic design types. This system represents a hypothetical aircraft electrical power system. The aircraft has two jet engines, each of which powers two electrical generators via bleed air from the engines. A minimum of two generators are required for aircraft electrical power. The system starts with generators G1 and G2 operating. Should the monitors detect loss of electrical power, the computer turns on generator G3 and then G4 if necessary. A minimum of two of the three monitors is required for successful operation. Each generator also has internal fault monitoring data which it sends back to the computer, so that the computer can turn on the necessary backup generators.

- Engines
  - E1
  - E2

- Generators
  - G1
  - G3
  - G2
  - G4

- Monitors
  - M1
  - M2
  - M3

Computer

**INSUFFICIENT ELECTRICAL POWER**

- TOP
  - LOSS OF 3 OF 4 GENERATORS
    - M1
    - G1 FAILS WHILE G2 WORKS OKAY
      - M2
      - G1 FAILS
        - M3
        - BOTH G1 AND G2 FAIL

- MULTIPLE CABLE FAULTS CAUSE LOSS OF ELECTRICAL POWER

Page 2
This example system has 10 components, most of which can be considered as 2-state (Working, Failed). The Generators G3 and G4 are 3-state (Working, Standby, Failed). This system results in a total of 2,304 states. This is without even considering other failure possibilities, such as cables, connectors, etc. Creating a Markov diagram for this many states is very difficult and very error prone, and a Markov solution could only be obtained if numerical methods were used. This problem is very easily modeled and solved using the Fault Tree, and although the results are an approximation, the results are valuable enough because when small probabilities are involved, pin point precision becomes relative and meaningless. An answer of $1.3 \times 10^{-7}$ is just as meaningful as $1.21153 \times 10^{-9}$.

Notice that Warm Standby and Cold Standby can be modeled without using special gates. This is because these modes are not dependencies, they are merely modes with different failure rates with different exposure times.
The Reliability viewpoint vs. the Safety viewpoint
One of the primary considerations in performing FTA or MA is the criticality nature of the problem. That is, is the Undesired Event a safety critical problem with catastrophic results, or is it merely a question of unavailability without any significant safety consequence.

The Reliability viewpoint:
- Non-catastrophic model
- Evaluation for system not being available when needed (Unavailability)
- Repair is often possible even when top UE occurs
- Example: Undesired State = Reactor Emergency Core Cooling System Not Available

The Safety viewpoint:
- Generally a catastrophic model
- Once the top UE occurs repair is not possible, a point of no return has been exceeded
- Example: Undesired State = Inadvertent Weapon Release

Conclusion:
- These two viewpoints have a significant impact on the analysis importance
- Repair of the last failure is not possible for the catastrophic safety case
- The catastrophic problem requires that all potential root causes be included in the model
- FT’s can model catastrophic Undesired States much more accurately than MA because FT’s can easily include such events as wire shorts, EMI, RF interference, human error, etc.
- MA does not easily model all types of fault conditions, and when it does the model becomes intractable, or incorrect if events are left out in order to simplify the model

FTA Attributes vs. MA Attributes
FTA and MA each have unique characteristics and attributes, in addition to common attributes. The following summarizes the particular attributes of each.

Markov Attributes:
- Handles event dependencies
- Handles repair
- The transition rates may not always be constant as assumed
- Assuming the system’s history is not important may not always be valid
- Can only model the undesired state of being “Failed”
- Is not a root cause analysis tool
- Can easily overlook and omit causes
- Can only handle small models (about 5 states) unless numerical methods are used
- MA cannot model secondary failure causes, whereas can FTA
- Models are not documented and can be confusing when large
- Large models are difficult to validate

FTA Attributes:
- FTA is a root cause analysis tool
- Models fault combinations and relationships
- Can model more undesired states than just “Failed” state
- Can approximate event dependencies
- Can approximate repair
- Can handle very, very large models
- FTA has a structured process making it difficult to leave root causes out
- Easy to modify as design changes
- Easy to validate
- Excellent for documentation
- Produces Importance measures which identify critical items
Conclusion:
- FT's provide more versatility
  handles larger systems
  can model any Undesired Event
  models root causes and their probabilities
  accurate for most design types, approximations are accurate enough for the rest
  provides Importance measures that identify weak links
  can model environmental effects such as weather
  can model secondary faults such as wire shorts, EMI, RF energy, etc.
  can model human error
  can model software error
- The FT model itself can identify weak system links even without resorting to probabilities
- Quite often the MA is really only an approximation, because many contributing fault events are ignored or left out in order to simplify the model
- When working with small numbers, approximations are generally good enough, thereby making FTA satisfactory when the models become approximations
- When the numbers are large, the results between MA and FTA are still very comparable, as shown in Figure 1.

Table 8 summarizes the capabilities and differences between FTA and MA.

<table>
<thead>
<tr>
<th>Consideration</th>
<th>FTA</th>
<th>MA</th>
</tr>
</thead>
<tbody>
<tr>
<td>1) Models Undesired Events</td>
<td>X</td>
<td>Partially</td>
</tr>
<tr>
<td>2) Models Probability</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>3) Models Unavailability</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>4) Series System</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>5) Parallel System</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>6) Full Monitor System</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>7) Partial Monitor System</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>8) Standby Redundancy System</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>9) Repair</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>10) latency</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>11) Dependency</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>12) Large models</td>
<td>X</td>
<td>No</td>
</tr>
<tr>
<td>13) Coverage</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>14) Easy to follow model</td>
<td>X</td>
<td>No</td>
</tr>
<tr>
<td>15) Easy to document process</td>
<td>X</td>
<td>No</td>
</tr>
</tbody>
</table>

BIography

Dr John Andrews  
Department of Mathematical Sciences  
Loughborough University  
Loughborough  
Leicestershire  
LE11 3TU  
England  

tele: +44 (0)1509 222862  
fax: +44 (0)1509 223969  
email: J.D.Andrews@lboro.ac.uk
Dr. Andrews is a Senior Lecturer in the Department of Mathematical Sciences at Loughborough University. He joined this department in 1989 having previously gained nine years industrial experience at British Gas and two years lecturing experience at the University of Central England.

His current research interests concern the assessment of the safety and risks of potentially hazardous industrial systems. This research has been heavily supported by funding from industry. Recent grants have been secured from Mobil North Sea Ltd, Daimler Chrysler and Rolls Royce Aero Engines.

Clifton A. Ericson II  
The Boeing Company  
18247 150th Ave SE  
Renton, WA 98058 USA  
phone 253-657-5245  
fax 253-657-2585  
email clifton.a.ericson@boeing.com  
cliftonericson@cs.com

Mr. Ericson works in System Safety Engineering on Boeing AWACS programs. He has 34 years experience in system safety and software design with the Boeing Company. He has been involved in all aspects of fault tree development since 1965, including analysis, computation, multi-phase simulation, plotting, documentation, training and programming. He has performed Fault Tree Analysis on Minuteman, SRAM, ALCM, Apollo, Morgantown Personal Rapid Transit, B-1, AWACS and 737/757/767 systems. He is the developer of the MPTREE, SAF and FTAB fault tree computer programs. In 1975 he helped start the software safety discipline, and has written papers on software safety and taught software safety at the University of Washington. Mr. Ericson holds a BSEE from the University of Washington and an MBA from Seattle University. He is currently Executive Vice President of the System Safety Society, and is on the technical review committee for the Journal of System Safety and the Journal of Process Mechanical Engineering (UK).